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Phase Object Display by using acousto-optical Bragg Diffraction

by

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HUMAN TRANSLATION

NAIC-ID(RS)T-0410-94 23 February 1995

MICROFICHE NR:

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English pages: 9

Source: GUANGXUE XUEBAO, VOL 10, NR 10, OCTOBER 1990

Country of origin: CHINA
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TABLE OF CONTENTS

Graphics Disclaimer i

Table of Contents ii

Phase Object Display By Using Acousto-Optical 1

PHASE OBJECT DISPLAY BY USING ACOUSTO-OPTICAL BRAGG DIFFRACTION

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Abstract: Based on the method of phase object display, this article proposes the possibility of showing the phase gradient of an object that can be realized by the acousto-optical Bragg diffraction. Mathematical formulas are derived and a discussion is presented.

Key words: Bragg diffraction, phase object, phase gradient.

I. Foreword

Acousto-optics and its application technology were active in the seventies. In order to provide the possibility of executing real-time processing of optical information, a wider range of information processing with the optical method has been realized. Based on the present-day phase object display method [1,2], this paper applies the acousto-optical Bragg diffraction effect so that the invisible phase distribution is converted into an observable intensity distribution, thus presenting another display method, the acousto-optical method for this category of objects. Moreover, the article presents the advantages of this method and the feasibility of real-time processing.

II. Derivation of Formulas

A phase object is an object with spatial and temporal structural configurations. For sake of convenience, this article mainly analyzes phase objects with spatial structure; the time-varying structure processing will be qualitatively described as to the feasibility of real-time processing. By using the acousto-optical interaction to demonstrate the phase object, this approach is based on the angular selectivity of acousto-optical Bragg diffraction. In other words, since there are different extents of momentum mismatch ($\Delta K_{\pm} \neq 0$), there are different diffraction efficiencies or intensities for diffraction incident angles at different spatial frequencies of the object. A concrete analysis is conducted in the following.

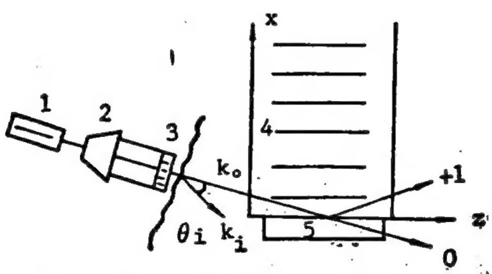

Fig. 1 Schematic diagram of acousto-optical mutual function

1—laser; 2—beam expander; 3—phase object 4—acousto-optical pool; 5—transducer

Fig. 1 shows incident onto an acousto-optical pool at angle theta of a monochromatic plane interference optical wave after passing through a phase object. Then the modulated optical field $E_i(x)=E_0\exp[i\varphi(x)]$, after passing through the phase object, appears on surface z=0 in front of the acousto-optical pool as

$$E_i(x)=E_0\exp[i\varphi(x)]\exp(ik_0\theta x)$$
$$=E_0\left[1+i\varphi(x)-\frac{\varphi^2(x)}{2!}-\frac{i\varphi^3(x)}{3!}+\frac{\varphi^4(x)}{4!}\cdots\right]\exp(ik_0\theta x), \quad (1)$$

Other than the first term of Eq. (1), the remaining terms indicate the complex wavefronts. To reduce the complexity and to avoid inconveniences brought about by nonlinearity in measurement

and testing, only linear terms are selected, because these terms make the main contribution to the image plane. By assuming $\varphi(x) \ll 1$ (actually it is appropriate for $\varphi(x) < 1\text{rad}$), Eq. (1) can be rewritten as Eq. (2):

$$E_i(x) = E_0[1 + i\varphi(x)]\exp(ik_0\theta x), \tag{2}$$

In Eq. (2), $\varphi(x)$ is the phase variation due to the optical path points when light passes through the phase object. Generally, this is a nonperiodic function. However, generally the limited dimension d_0 of the object can be considered as a spatial period so that there is a $\varphi(x)$ in each repeated d_0, thus, $\varphi(x)$ can be processed as a periodic function. In the analysis, let us assume

$$\varphi(x) = \varphi_0 \cos\left(\frac{2\pi x}{d_0}\right)。 \tag{3}$$

By substituting Eq. (3) into Eq. (2), we obtain

$$E_i(x) = E_0\left[1 + i\frac{\varphi_0}{2}\exp\left(i\frac{2\pi x}{d_0}\right) + i\frac{\varphi_0}{2}\exp\left(-i\frac{2\pi x}{d_0}\right)\right]\exp(ik_0\theta x)。 \tag{4}$$

This is a complex field distributed input with fundamental frequency $(1/d_0)$; there is a plane wave phase factor. By making a Fourier analysis, the input can be resolved into many diffraction components along different directions and different diffraction angles θ_i (relative to incident direction $\mathbf{k}_0$). In other words, as shown in Fig. 1, resolve along plane waves with different directions of propagation $\mathbf{k}_i$. The diffraction of any plane wave passing through the acousto-optical pool can be described by the coupling equation of acousto-optical interaction. In the situation that the main supersonic direction is perpendicular to the surface of the transducer, a normal Bragg diffraction coupling wave equation has the following resolution [4].

$$\left.\begin{aligned}
&E_0(z)=E_0\exp\left(-i\frac{\zeta z}{L}\right)\left[\cos\left(\frac{\sigma z}{L}\right)+i\frac{\zeta}{\sigma}\sin\left(\frac{\sigma z}{L}\right)\right],\\
&E_+(z)=E_0\exp\left(-i\frac{\zeta z}{L}\right)\frac{\xi}{2\sigma}\sin\left(\frac{\sigma z}{L}\right),\\
&\sigma^2=\zeta^2+(\xi/2)^2,\quad \zeta=-\frac{1}{2}\Delta k_{+1}L,\\
&\Delta k_{+1}=\frac{K}{\cos\theta_0}\left[\frac{K}{2k}-\sin\theta_0\right],\\
&K=(2\pi/\Lambda),\quad k=(2\pi n/\lambda_0),
\end{aligned}\right\}\tag{5}$$

In these equations, ξ is the wave parameter; it indicates the intensity of acousto-optical interaction; L is the length of interaction; K and k represent the wave number of supersonic and optical waves, respectively; θ_0 is the angle of incidence onto the acousto-optical pool by any plane wave component; this is also called the adjustment parameter, which is determined by adjusting the direction of the acousto-optical pool. Apparently, in our problem it is

$$\theta_0=\theta+\alpha\theta_i,\quad (\alpha=0,\ \pm 1)\tag{6}$$

When the wave parameter ξ is very small (ξ<<1), in other words under the weak acousto-optical interaction, there is $\sigma \doteq \zeta$. At z=L, the complex oscillation amplitude of diffracted light is

$$E_{+1}(L)=E_0\exp(-i\zeta)\frac{\xi}{2}\sin C\sigma,\tag{7}$$

In the equation, (ξ/2)sin $C\sigma$ can be considered as oscillation amplitude transmissibility of the interactive medium. Based on the Kirchhoff approximation [5], the diffraction complex amplitude should be equal to the product of the incident complex oscillation amplitude multiplied by the oscillation amplitude transmissibility. Thus we obtain the result that the overall diffraction light field after passing through the acousto-optical pool is

$$E_d(x)=E_i(x)\frac{\xi}{2}\sin C\sigma,\tag{8}$$

The subscripts i and d indicate, respectively, incidence and diffraction. For convenience in observing the function of the diffraction components along different directions and with

different diffraction angles θ_i (satisfying the relation $\sin \theta_i = (\lambda / d_i)$, this is also the effect of reflecting different directions and different spatial frequencies $(1/d_i)$ of the object, the function sin $C\sigma$ is written in the form of an angular spectrum

$$\left.\begin{aligned} &\sin C\sigma = \sin C\left[\frac{\pi L}{\Lambda}(\theta_0 - \theta_B)\right], \\ &\sin \theta_B \cong \theta_B = \frac{\lambda_0}{2\pi\Lambda}, \ \sin\theta_0 \cong \theta_0, \end{aligned}\right\} \tag{9}$$

Substitute Eq. (6) in Eq. (9), and H_a indicates sin $C\sigma$ of different θ_i, then we have

$$H_a = \sin C\left[\frac{\pi L}{\Lambda}(\theta + \alpha\theta_i - \theta_B)\right], \quad (\alpha = 0, \pm 1) \tag{10}$$

Substitute Eqs. (4) and (10) in Eq. (8)

$$E_d(x) = E_0 \frac{\xi}{2}\left[H_0 + i\frac{\varphi_0}{2} H_{+1} \exp\left(i\frac{2\pi x}{d_0}\right) + i\frac{\varphi_0}{2} H_{-1} \exp\left(-i\frac{2\pi x}{d_0}\right) \exp(ik_0\theta x), \tag{11}$$

The corresponding intensities (neglecting those terms of higher than second order) are

$$\left.\begin{aligned} &I_d(x) = E_d(x)E_d^*(x) = E_0^2\left(\frac{\xi}{2}\right)^2 H_0^2\left[1 - \gamma\frac{d_0}{2\pi\varphi_0}\frac{d\varphi(x)}{dx}\right], \\ &\gamma = \varphi_0\frac{H_{-1} - H_{+1}}{H_0}, \end{aligned}\right\} \tag{12}$$

In the equations, γ is the contrast. As indicated by Eq. (12), the diffraction light intensity is proportional to the phase gradient. The phase information linearly modulates the light intensity distribution on the image plane, appearing as a graph with contrast. Thus, the feasibility of phase object display by the intended acousto-optical method is implemented.

III. Brief Discussion

As is well-known, image quality depends on image contrast; adjustment of the directional angle θ of the acousto-optical pool is closely related to contrast γ:

(1) When $\theta=\theta_B$, $H_{-1}=H_{+1}$, and contrast $\gamma=0$, there is no display.

(2) When $\theta=\theta_B\pm\Delta\theta$, contrast $\gamma\neq0$; in this case, the phase gradient display is feasible. In the equation, $\Delta\theta=(\Lambda/L)$ is the supersonic divergent angle; actually, this angle always exists in supersonic waves. The analysis is conducted as follows.

(i) For higher spatial frequencies $1/d_i$, the contrast is

$$\begin{aligned}\gamma&=\varphi_0\frac{H_{-1}-H_{+1}}{H_0}\\&=\varphi_0\frac{\sin C[(\pi L/\Lambda)(\theta-\theta_B-\theta_i)]-\sin C[(\pi L/\Lambda)(\theta-\theta_B+\theta_i)]}{\sin C[(\pi L/\Lambda)(\theta-\theta_B)]}\\&=2\varphi_0(\theta-\theta_B)\frac{\left(\frac{\lambda}{d_i}\right)\cos\frac{\pi L\lambda}{\Lambda d_i}(\theta-\theta_B)\operatorname{ctg}[(\pi L/\Lambda)(\theta-\theta_B)]\sin\left(\frac{\pi L\lambda}{\Lambda d_i}\right)}{(\theta-\theta_B)^2-(\lambda/d_i)^2}。\end{aligned}\tag{13}$$

When the nonuniformity of the supersonic intensity does not exceed 4dB within the working frequency range, there are $\delta\theta=\theta-\theta_B=0.5(\Lambda/L)$ [4] and $(\pi L/\Lambda)(\theta-\theta_B)=\pm(\pi/2)$. Eq. (13) is simplified into

$$\gamma=2\varphi_0(\theta-\theta_B)\frac{\left(\frac{\lambda}{d_i}\right)\cos\left(\frac{\pi L\lambda}{\Lambda d_i}\right)}{(\theta-\theta_B)^2-(\lambda/d_i)^2}。\tag{14}$$

Citing TeO_2 crystalline material as an example, when f=100MHz, λ=6328A and $\Lambda=(V/f)$=42.0micrometers; the characteristic length L_0=6.51mm. Let $L=2L_0$=13.02mm [4], and assume $d_i=10^{-2}$mm, by using 1rad in the calculation for φ_0 we obtain $\gamma=0.54>0.02$ (minimum contrast). We can see that the acousto-optical interaction system has higher spatial frequencies for displaying details of an object still with observable contrast.

(ii) At very low spatial frequencies $1/d_i$, by neglecting the term $(\lambda/d_i)^2$ and considering $\cos(\pi L\lambda/\Delta d_i)=1$, $\sin(\pi L\lambda/\Lambda d_i)\cong(\pi L\lambda/\Lambda d_i)$, Eq. (13) can be written as

$$\gamma=2\varphi_0\frac{\pi L\lambda}{\Lambda d_i}\left\{\frac{1}{(\pi L/\Lambda)(\theta-\theta_B)}-\operatorname{ctg}\left[\left(\frac{\pi L}{\Lambda}(\theta-\theta_B)\right)\right]\right\}。\tag{15}$$

When $\delta\theta=\theta-\theta_B=\pm0.5(\Lambda/L)$, Eq. (15) is further simplified as

$$\gamma = \varphi_0 \frac{4L\lambda}{\Delta d_t}。\quad (16)$$

We can see from Eq. (15) that when the adjustment parameter θ deviates only slight from angle θ_B, the absolute value of γ is very large. This explains that the acousto-optical pool is a very good low-throughput filter. The pool can provide large structure and crude profile of a high-contrast object. These features are interesting and beneficial to researchers.

From the above discussion, the acousto-optical interaction system has features of both the diffraction interference method and those of the filtration method, thus being capable of displaying phase gradient from low to high frequencies [6].

Next, to estimate the method sensitivity by citing an example of the above-mentioned assumption that the maximum limit of $\varphi(x)$ is 1rad, for the range of refringence difference for Δn between 0.05 and 0.0005, we know from the relation equation $L=(\lambda/2\pi)(\varphi/\Delta n)$, this method can be used to show the phase variation from micromillimeter (or smaller) magnitudes to thousands of a wavelength (or longer) magnitudes. This indicates that this method has prospects of wide application.

Since information is directly applied to the acousto-optical pool and is not applied to the transducer as is generally the case, therefore only with sufficient width of a coherent light beam width can this method be basically not limited by object dimensions (sector by sector processing can be conducted for an oversize object). Moreover, from the approach of vertical incidence, a three-dimensional display can be obtained for incidence into another coherent light source with another set of synchronous- variation acousto-optical devices. However, the maximum advantage of the acousto-optical method is its real-time processing of phase objects. In the method, with fast switching of supersonic frequencies at the transducer (switching should not

be less than the time for the supersonic wave to pass through), and adding in order for incident light source of different diffraction angles θ_i for display in sequence. However, in this method consideration should be given to overcome the limitation of the speed of sound, thus bringing up the difficulty of variation and focusing of diffraction deflecting angle brought by the nonuniform phase grating. Also, acousto-optical devices of multiple-plate structure can be adopted. By applying many frequencies at the transducer, real-time processing can be executed. At this point, the interaction situation is complicated so it is required to use multifrequency coupling wave equation [7] to describe and to seek the solution. Moreover, it is required to resolve the weakening of the first-stage diffraction light caused by interadjustment of various stages because of multiple acousto-optical diffractions.

Finally, when deducting the function assume $\varphi \ll 1$ and $\xi \ll 1$ in the derivations. In this approach, not only can the nonlinear analysis of the complex diffraction field be avoided, but also by directly applying the principle of iterative addition, a linear relation with practical significance can be obtained, thus proving the feasibility of the new method. As in practice, the optical field and the acoustic field are functions of time and space, the above-mentioned limitations are not necessary. However, in practical work, estimates should be made of the dynamic range of time and space functions with consideration of the effect of their nonlinearity on interaction.

The first draft was received on 30 June 1989; the final revised draft was received for publication on 15 May 1990.

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